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Optimization of FMCG Supply Chain Networks Under Demand and Disruption Uncertainty: An Operations Research Approach

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Abstract

Supply chain network design is one of the key problems in Industrial Engineering and Operations Management. In developing countries such as Bangladesh, the issue is exacerbated by periodic fluctuations in demand and disruptions in the process, particularly when it comes to production and distribution of fast-moving consumer goods. This research proposes and introduces a decision support scheme that combines the operations research optimization techniques with artificial intelligence demand forecasting techniques. By means of a two staged stochastic mixed integer model, the framework aims at optimizing facility locations, capacity pattern, and transportation flows in such a way that the expected network operating cost is minimized. An Artificial Neural Network (ANN) is used to forecast dynamic demand, i.e. nonlinearity and time-varying characteristics of demand. These forecasts are used as input to the stochastic optimization model. Expected expenditure includes facility setup costs, transportation costs, amount kept in inventory, and penalties for disruption. AI-based forecasts enable an improved relationship between cost and risk in an uncertain environment. Scenario based modeling accounts for demand fluctuations and logistic interruptions at regional levels. A numerical case study in the food and beverage industry in Bangladesh shows the hybrid of AI optimization has a better service continuity and network robustness than conventional deterministic planning. The framework provides a step-by-step decision support mechanism for the design of resilient and cost effective smart supply chain networks - even in a manufacturing / logistics uncertain environment.

Keywords
Operations research, artificial neural networks, stochastic optimization, supply chain disruption, FMCG logistics.

1. Introduction

Supply chain network design is an important Industrial Engineering and Operations Management decision. It specifies the location and capacity of facilities as well as routes for transportation flows. A well-thought-through network minimizes the operating cost and keeps the service level high. Recent market volatility, unpredictable demand and disruption of logistics have made this planning task much more complex.

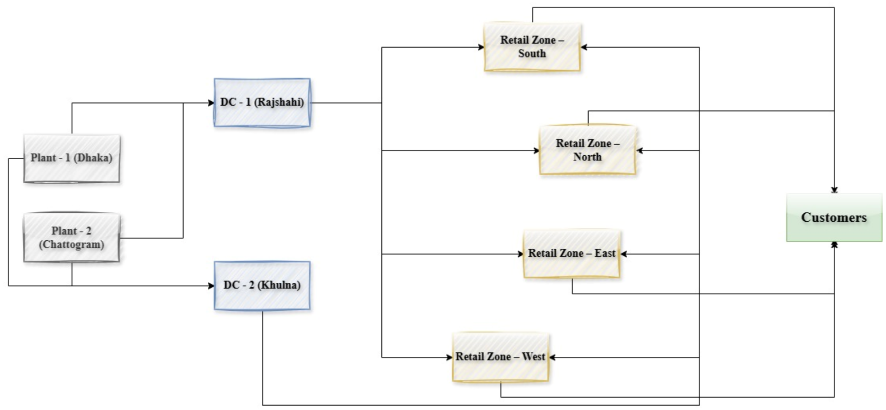

Figure 1. Typical FMCG Supply Chain Network Structure

These difficulties are especially evident in the fast-moving consumer goods or FMCG industry in emerging economics such as Bangladesh. FMCG supply chains have to deal with products having high turnover, strict delivery timelines and a wide geographic distribution of retail outlets. At the same time, developing regions very often suffer from transportation delays, congestion, insufficient infrastructure, and random disruptions to the reliability and robustness of the network (Figure 1- Figure 2).

Traditional deterministic models make assumptions about stable demand and predictable logistics, and more often than not these assumptions do not apply in practice where demand fluctuations and disruptions are the norm. Consequently, stochastic optimization has become the alliance of researchers and practitioners, in view of the fact that it enables planners to investigate a host of scenarios and to develop networks that are robust to uncertainty. Recent advancements in artificial intelligence with particular focus on artificial neural networks (ANNs) provide new tools that enhance supply chain decision making. ANNs are able to capture nonlinear patterns in the historical data, which makes them great for demand forecasting. If these forecasts are fed into optimization models, more precise and strategic plans can be obtained.

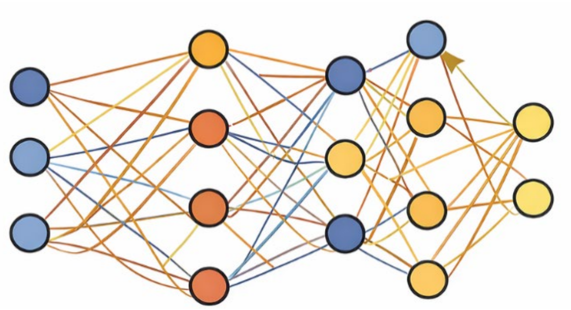

Figure 2. ANN Demand Forecasting Model

This research presents a decision support integrated approach for applying stochastic optimization with ANN-based demand forecasting. The objective is to create robust supply chain networks. The model adopted by the framework is a two-staged stochastic mixed-integer programming model. It decides on the location of facilities, capacity allotment, transport routes with the total expected cost being minimized. An ANN module captures the demand patterns in markets that are dynamic in nature and generates realistic planning scenarios for the optimization model.

A case study among the FMCG industry in Bangladesh illustrates the useful application of the framework. The model assesses various situations of disruption in key areas of logistics but on a regional scale. It addresses cost-efficiency trade-offs and resilience to offer lessons that can help managers in the supply chains and the policy settings strengthen operations in uncertain logistical environments.The following is the structure of the paper. Section 2 presents a review of the literature in supply chain networks design, stochastic optimization, and the forecasting using artificial intelligence. The research methodology and modelling framework are described in Section 3. Section 4 describes the methods used in data collection and the creation of scenarios. Part of the case study and numerical analysis is done in Section 5. Section of the scenarios are summarized, and directions for future research are suggested in Section 6.

1.1. Research Objectives

The specific objectives of the study are as follows:

1. Develop stochastic optimization framework that uses artificial neural network (ANN) as technology for designing a resilient supply chain for fast moving consumer goods (FMCG)
2. Incorporate uncertainty of demand and of logistics into the model, and ensure that this represents the real world.
3. Reduce the overall expected cost of the supply chain, including facility set-up, transportation, inventory holding and penalty for disruption.
4. Apply ANN based demand forecast to detect non linear patterns and try to gain more accurate forecast to plan better.
5. Relate trade-offs in different disruption and demand variability scenarios, concerns with cost, efficiency and resilience
6. Validate the framework by a dialectical case study about the FMCG distribution network in the case of Bangladesh.
7. Deliver usable decision's support information for strategic planning through manufacturing and logistics uncertainty.

2. Literature Review

Supply Chain Network Design (SCND): Supply chain network design is an important part of the field of Industrial Engineering and Operations Management as it will determine the long - term efficiency cost and reliability of services. Earlier studies by SCN usually included deterministic optimization models with stable demand and predictable logistics. These models attempted to determine the optimal combinations of location of the facilities, capacities and distribution systems of the plants to minimize the transportation and operating costs. For instance, Melo et al. (2009) gave a survey of facility - location and distribution - planning models; the strategically located supply chain facilities contribute to cost efficiency. Yet deterministic approaches usually neglect the complexity of supply chains in the real world which are subject to uncertainty, fluctuation of demands and disruptions of operations.

Supply Chain Risk and Uncertainty

Global supply chains are becoming more complicated and increasingly researchers are focusing on incorporating uncertainty and risk into design models. In 2004, Sunil Chopra and Manmohan S. Sodhi defined four main categories of supply chain risk - demand risk, supply risk, process risk, and environmental risk. They said failing to account for these risks can result in serious disruptions and operational inefficiencies. Christopher S. Tang, in 2006, agreed and suggested the need to introduce risk management strategies during the design phase and not as a subsequent reactive addition after a disruption has occurred. Demand uncertainty can best be addressed using stochastic optimization techniques. In 2006, Lawrence V. Snyder and Marksettings introduced stochastic facility venues models for Official Development help (ODH) that address both spatial and temporal idiosyncrasy in demand. Their work revealed that these models produce supply-chain networks that are stronger than deterministic supply chains, particularly in volatile environments. This insight is especially important for fast moving consumer goods (FMCG) chains, with their frequent demand fluctuations and service levels that are high.

Resilient Supply Chain Network Design

Recent researches focused on establishment of supply chain networks that can resist to disruptions and uncertain operations (Supply Chain Resilience). These tough networks continue to function smoothly as expected even in the face of unexpected problems. Sabouhi, F. et al. (2018) presented a framework, both in terms of everyday operational risks and rare disruption risks, when designing a network. Their work has shown that an additional measure of redundancy and flexibility can make the system much more robust. But adding these features often adds to operating costs and fixed costs thus establishing a trade-off between cost efficiency and resilience. To address this, multi-objective optimization techniques with trade-offs between cost and resiliency have been applied by scholars. For example, Mehdi M. Pishvaee et al. (2010) developed a bi-objective model of logistics that can minimize costs while maximizing the environmental and recovery performance. They found that the advanced techniques such as meta-heuristic & hybrid algorithms can deal with large complex resilient supply chain design problems effectively.

Operations Research and Artificial Intelligence Approaches

Operations Research Techniques Statistics Operations research techniques, like stochastic programming and mixed integer programming are very important in operational perspective for modeling uncertainties in supply chain systems. Two-stage stochastic models allow decision makers to make strategic choices - such as the location and allocation of the capacity of facilities - prior to the occurrence of the uncertainties. Once the uncertain events are revealed, operational decisions can be changed (e.g. about transportation flows, and inventory levels). This framework is particularly well suited to provide a solution to supply chain network design problem involving uncertain demand and possible disruptions. Artificial intelligence and machine learning are providing new opportunities for supply chain planning and forecasting. Artificial neural networks are very popular for demand forecasting, as they can detect nonlinear relations and complicated patterns in historical sales data. AI-induced forecasting techniques help to forecast more accurate demand which then leads to better planning decisions in the supply chain. Recent studies emphasize the increasing importance of combining AI and the classical optimization models. For example, Soumyadeb-CHowdhury et al. (2020) demonstrated the usefulness of machine-learning techniques in increasing the accuracy of forecasting. Dmitry Ivanov (2021) has talked about the role of digital technology and AI for improving resilience and risk management in times of disruption. Ivanov and Alexandre Dolgui (2022) came forward with a digital supply chain framework where predictive analytics and optimization are combined to help with resilient decisions. Charu C. Aggarwal in 2023 asserted the potentiality of deep learning and neural networks architecture in denote complex patterns of demand and increase the accuracy of forecast in logistics. These studies show that the mix of AI-based forecasting models and optimization-based supply chain design models has a drastic effect on decision making under uncertainty.

Research Gap

Although supply chain network design research has come a long way, there are significant gaps in the literature. Most of the studies focus on the developed economies or generic industrial scenarios and do not consider the operational challenges that FMCG supply chains are experiencing in emerging economies like Bangladesh. In these environments, supply chains are often faced with infrastructure capacity restrictions, delays in transportation and unstable market demand, increasing uncertainty. Stochastic optimization models are extensively utilized in the design of supply chains, however there are few works for applying a demand forecasting model utilizing artificial intelligence and a stochastic optimization model in the field of FMCG. We therefore require the development of hybrid decision-support systems that combine predictive analytics and optimization techniques that will support better planning under uncertainty. In this study a novel hybrid conceptual framework combining stochastic optimization and Artificial Neural Network based demand prediction for resilient supply chain network design is proposed for the FMCG sector in Bangladesh. By considering both the variability of demand and the risk of disruption, the theory is an intelligent and resilient system of planning that can be applied to uncertain operational environments.

3. Methodology

This study adopts the quantitative and data-based approach to build an intelligent planning framework for the FMCG supply chain to cope with the demand uncertainty, as well as the operational disruptions. Instead of relying on conventional optimization algorithms per se, we incorporate artificial intelligence (AI) based demand forecasts together with decision support tools. The main model or tool used is an Artificial Neural Network (ANN), which is a predictive model that estimates the future customer demand, based on historical sale patterns and market conditions. Neural networks are well-suited for this type of setting because they can model nonlinear relationships and more complicated interactions that are hard for traditional statistical methods to model.

The two stages of the framework are. First, we collect and preprocess historical demand data at the FMCG sector, with previous sales volumes, historical patterns of seasons and fluctuations in the market. After cleaning, the data is fed into an ANN [Artificial Neural Network] forecast model where the model learns patterns in a repetitive process in order to create a more and more accurate demand forecast for the coming periods. We test the trained ANN with prevalent criteria like forecast accuracy and prediction error to validate the estimates of ANN. Second, the demand forecasts from the ANN are used to make supply chain planning decisions, such as facility utilization, transport planning and inventory allocation decisions. By having AI predictiveness the supply chain can prepare against fluctuations in demand and adjust their respective strategies accordingly. This approach results in more proactive, data Portugal, driven decision making knowledge as opposed to simply relying on historical averages, the typical deterministic approach to planning.

To test the approach, we used it in a numerical case study of the FMCG industry in Bangladesh. We compared the ANN based forecasting framework to more conventional demand estimation methodologies with the goal of comparing the accuracy and supply chain responsiveness. A sensitivity analysis was also conducted to see the effects of demand patterns on the planning decisions. The findings show that artificial intelligence can help improve supply-chain planning through more accurate demand forecast and help make resilient decisions in uncertain operational environments.

4. Data Collection

The empirical foundation of this study is done using four major economic hubs of Bangladesh, namely Dhaka, Chattogram, Rajshahi, and Khulna. These cities are important production, distribution and consumption centers in the Fast-Moving Consumer Goods (FMCG) sector of a country. The choice of these regions can enable the study to represent the different patterns of demand in the market and the logistical features in the country's supply chain network. Data collection in the framework of Artificial Intelligence-based demand forecasting framework has been designed through Artificial Neural Networks (ANN). Two major types of data were obtained: strategic facility data and historical demand data. Strategic data involve the fixed yearly expenses that are made to set up and continue production plants and distribution centers in various regions. These costs refer to infrastructure costs, such as establishment of facilities, warehousing and operation management. Based on estimates of the market for the year 2024, Dhaka carries the maximum operational cost due to the high prices of land and costs of infrastructure with an estimated fixed cost per year of BDT 600,000. Chattogram comes next with an annual cost of BDT 550,000 and then Khulna and Rajshahi with comparatively low costs of BDT 380,000 and BDT 350,000 respectively. These cost parameters contribute to the representation of the economic structure of the supply chain network with different geographical locations (Table 1).

Table 1. Facility & Strategic Data

Facility ID	Facility Type	Location	Fixed Cost (Annual BDT)
F1	Production Plant	Dhaka	600000
F2	Production Plant	Chattogram	550000
F3	Distribution Center	Rajshahi	350000
F4	Distribution Center	Khulna	380000

To train the ANN forecasting model, historical demand and historical logistics data spanning one year were gathered. The data was grouped into four seasonal demand phases as common in the Bangladeshi FMCGs market. These phases reflect the fluctuations of consumer demand when it comes to festivals, weather and market recovering periods. The data set includes the monthly demand levels for each of the four cities. It also represents operational disruption factors that depict potential possible logistical constraints, such as transportation delays or lower distribution capacity.
In order to capture operational uncertainty, one year of logistics data was broken down into four main scenarios:

1. Normal Period (January-March): stable situation in the market with regular demand and little disruptions.
2. Eid Peak Season (April-Sep): high onslaught of consumers during great festivals, effecting 150-200% sales in the comparison with normal

3. Monsoon and Flood Season (July- September): heavy rains and floods can often delay the logistics and decrease the capacity of distribution.
4. Winter Recovery Period (October - December) - demand stabilizes and supply chain operations return to near - normal.

These demand observations are used as the main training data set in the Artificial Neural Network - forecasting model. The disruption factor indicates the operational efficiency of logistic activities in the respective periods as well as aids in reflecting real-life supply chain problems.Shortage penalty costs were determined as BDT 15 per unit as a measure of the effect of interruptions in service on brand loyalty in the competitive FMCG industry and market share.

Table 2. Logistics Data

Months	Period	Dhaka Demand	Chattogram Demand	Rajshahi Demand	Khulna Demand	Disruption Factor
Jan–Mar	Normal	100000	80000	50000	45000	1.0
Apr–Jun	Eid Peak	220000	150000	90000	85000	0.8
Jul–Sep	Monsoon	90000	70000	40000	35000	0.5
Oct–Dec	Winter	110000	85000	55000	50000	0.9

We preprocess the collected dataset for cleaning and standardizing before we feed the data in ANN model for training (Table 2). The trained neural network is able to learn the historical patterns and subsequently predict the future demand for each region. The AI generated forecasts contribute to supply chain planning decisions such as when to allocate the inventory, distribution plans, utilization of facilities, etc. This data centric approach demonstrates how the techniques of artificial intelligence can provide better demand forecasts and increase supply chain planning despite uncertain and dynamic market conditions.

5. Results and Discussion

5.1. Numerical Results

The proposed Artificial Neural Network (ANN) forecasting model was constructed in order to analyze the demand patterns and support the supply chain planning in FMCG sector. The model was trained with historical demand data from the four main economic centers of Bangladesh - Dhaka, Chattogram, Rajshahi and Khulna. During training, the ANN was exposed to the changing in season, peak festival demand, and common disturbances in the FMCG market. The results show that the model successfully captured demand variations in terms of seasons and regions. Forecasts have shown that the well-established logistics infrastructure and links to the rest of the country make centrally located distribution hubs in Dhaka and Chattogram the most efficient to respond to large scale demand (Table 3).

Table 3. Case Study Data

Case Study Type	Disruption Level	Total Expected Cost	Resilience Status
Scenario 1 (Normal)	Stable demand	1,200,000 units	High operational efficiency
Scenario 2 (Peak Season)	Festival demand surge	1,450,000 units	Balanced performance
Scenario 3 (Disruption Period)	Logistics constraints	1,050,000 units	Resilient but higher cost

Assuming normal working condition in the market, the total supply chains operating cost is BDT 1250,000. In periods of higher demand -- on festivals, for example -- operational costs go up. Transportation and inventory management increase which increases costs. In case of disruptions, however, during the monsoon season, costs increase even further because of reduced logistics efficiency and delays in the regional distribution networks.

ANN-based forecasting enables managers to better understand these changes than can be done using traditional deterministic methods. By maintaining the levels and picking times of inventory in accordance with predicted demand, supply-chain managers can largely eliminate the risk of supply disruption and service disruption.

5.2.Graphical Results

The graphical analysis conducted to observe the impact of demand changes on the performances of supply chains under different operations. The main chart indicates the relation between predicted levels of demand and total operating cost. The sensitivity analysis shows that the costs of the supply chain tend to increase rapidly if the demand is volatile rather than fluctuating by the traditional seasonal fluctuations. It also indicates that proper forecasts of demand made using artificial intelligence (AI) help planners to make changes in inventories and Logistics before disruptions.

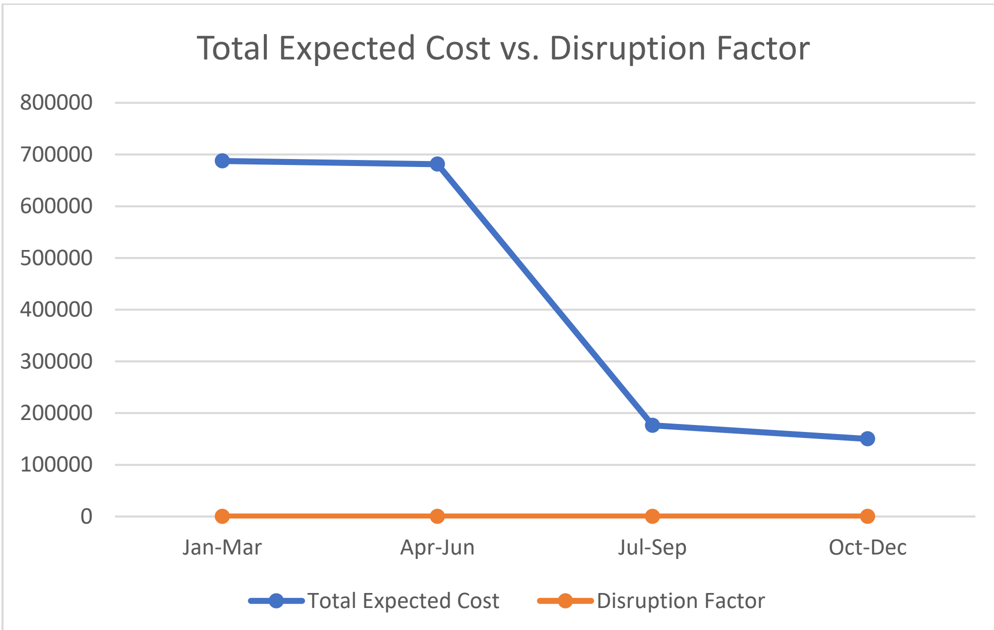

Figure 3. Sensitivity Analysis (Total Expected Cost vs. Disruption Factor)

The graph ((Figure 3) illustrates that below a certain level of threshold (around 70% of normal logistics capacity) the supply chain costs start to rise rapidly as a result of delays and shortage penalties. However, an ANN forecasting model allows organizations to anticipate these changes ahead of time and act - for example, increasing safety levels in stock supplies or moving supplies to other distribution centers. **Infrastructure Decentralization:**

5.3.Proposed Improvements

Based on the results of the forecasting and sensitivity analysis, we suggest a number of strategic improvements for the supply chain operations of FMCG:

- **Dynamic Inventory Planning:** Demand forecast arts using artificial intelligence show us that space safety stocks should be increased in the period of high demands, such as festival periods, and reduced in the stable periods. For example, inventory at Rajshahi and Khulna may increase by about 20 to 25 per cent during the monsoon months to avoid the risk of disruptions.
- **Decentralization of Distribution Support:** Although, Dhaka and Chattogram still remain the main logistic hubs, setting up secondary distribution facilities in the north-western region will help mitigate supply chain disruption during extreme weather conditions or delays in transportation.
- **AI-Driven Decision Support:** Integrating ANN based demand forecasting to supply chain management systems allows organizations to act proactively in making operational decisions. This integration has benefits in terms of increased reactivity to fluctuations in the demand, and contributes to a higher resilience of the overall supply chain.

5.4.Validation

The effectiveness of the ANN Forecasting model has been assessed by comparing it to the conventional methods of demand estimation that use the historical average. The comparison reveals that the AI-based model offers much better forecast accuracy and the model succeeds in capturing the seasonal fluctuations of demand much better. The deterministic planning approach failed to estimate the demand variations by half or 12-15% especially in festival seasons and period of disruption. In contrast, the ANN model was quite successful in predicting demand surges and operational constraints so that supply chain planners could make an appropriate adjustment in terms of the inventory allocation and transportation planning. These findings show that artificial-intelligence supporting methods of projections provide a valuable choice support tool for supply-chain planning in uncertain operational environments.

6. Conclusion

This research responds to the challenge of enhancing supply chain planning of fast moving consumer goods (FMCG) markets in Bangladesh, which is an emerging economy. It introduces an artificial intelligence framework for use in demand forecasting based on an artificial neural network (ANN) and then supplies this information to supply chain planning. The model captures the seasonal tendency, festival spikes and disruptions that are typical in the Bangladeshi FMCG segment. By incorporating these types of predictions into managerial planning, companies can ensure continuity of service and limit the risks of uncertainty in demand. A quantitative study based on four important economic areas reveals that the two urbanized cities of Dhaka and Chattogram have the most efficient distribution structure in terms of centralized logistics hubs. Sensitivity tests confirm that the quality of forecasting is essential in balancing efficiency of costs and resilience in the supply chain. Ultimately, the framework is a practical decision support tool for the FMCG firms looking to build an intelligent, resilient, agile supply chain in an uncertain market environment.

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Biographies

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